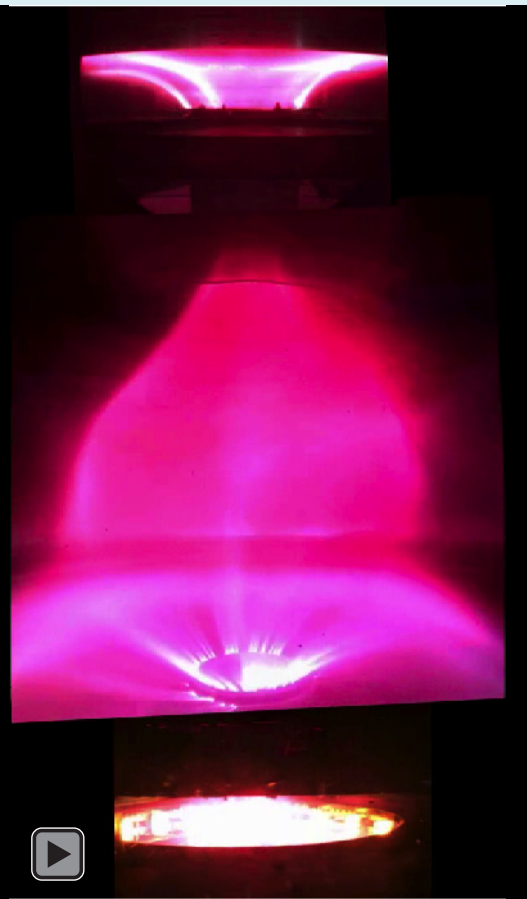


Final results of the Phase-1 of the PROTO-SPHERA experiment and first evidences of plasma tori production and sustainment

Paolo Micozzi and PROTO-SPHERA Group



PROTO-SPHERA



Crab Nebula remnant

PROTO-SPHERA Group

FSN Department, CR-ENEA Frascati

Franco Alladio, Paolo Micozzi, Alessandro Mancuso^{retired}, Vincenzo Zanza^{retired},
Fabrizio Andreoli, Gerarda Apruzzese, Luca Boncagni, Paolo Buratti, Fabio Crescenzi,
Ocletto D'Arcangelo, Edmondo Giovannozzi, Luigi Andrea Grosso, Alessandro Lampasi,
Violeta Lazic, Simone Magagnino, Valerio Piergotti, Mario Pillon, Selanna Roccella,
Giuliano Rocchi, Alessandro Sibio, Benedetto Tilia, Angelo Tuccillo, Onofrio Tudisco

FSN Department, CREATE Consortium and retired from CR-ENEA Frascati

Giuseppe Maffia

FSN Department, CREATE Consortium, Physics Department Università Roma-1, la Sapienza
Brunello Tirozzi

PlasmaTech Spin-off of Pisa University and Pisa University

Francesco Giammanco, Paolo Marsili

Pisa University

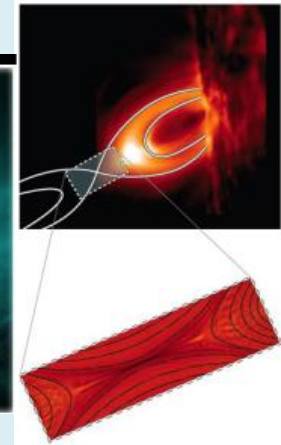
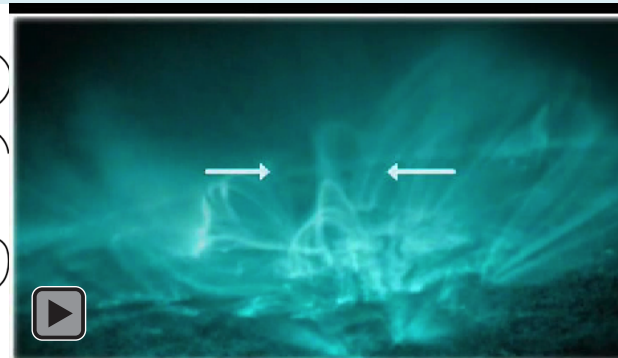
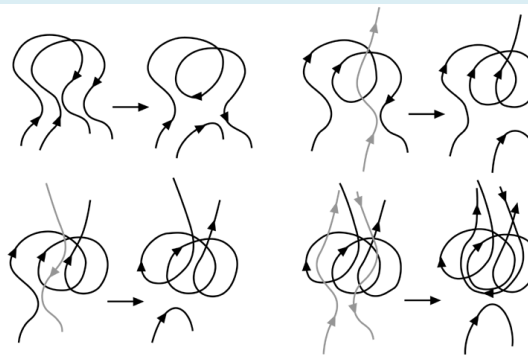
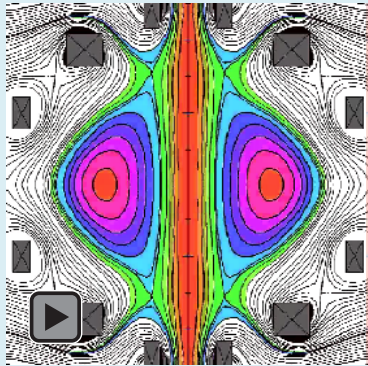
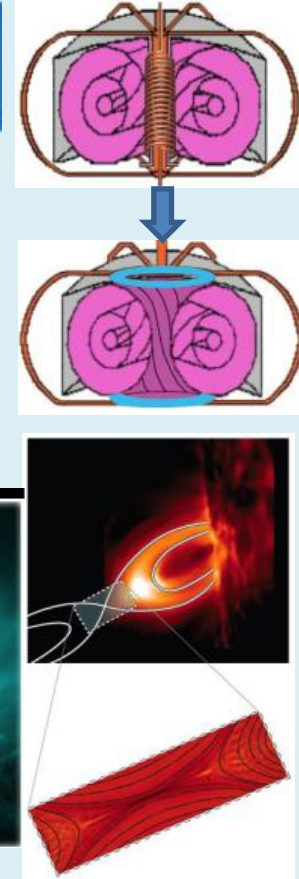
Danilo Giulietti

Università di Padova e Consorzio RFX and FSN Department, CR-ENEA Frascati

Giuseppe Galatola Teka, Matteo Iafrati

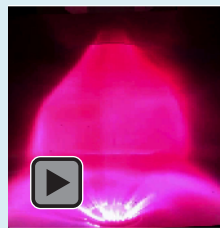
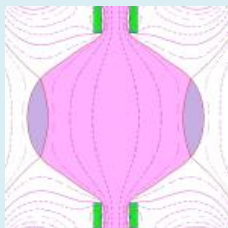
SUMMARY

- PROTO-SPHERA replaces the central metal conductors of Tokamaks by a Centerpost Plasma (with helically wound B lines) feed by electrodes
- Underlying physics is the «magnetic reconnections of a plasma». At ordinary magnetic field X-points, they transfer magnetic flux & electric current: magnetic field energy converts to plasma temperature

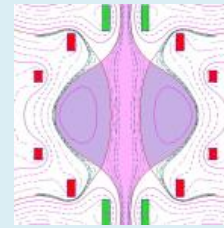


- In Phase-1 (2018) the obtained plasma tori, filled 7% of the total plasma volume. In Phase-1.5 (2019), 6 new magnetic coils are being inserted inside a new insulating vacuum chamber, the spherical tori could fill up to 70% of the plasma volume. Phase-2 aims to fill up to 95%: power densities $\sim 100 \text{ MW/m}^3$ $\sim$ fission reactors

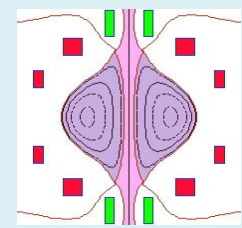
2018
2.5 MW



2019
3.5 MW



2021
 $\sim 20 \text{ MW}$



PROTO-SPHERA gets rid of 2nd Magnetic Confinement basic tool



Gas-puffed
Anode

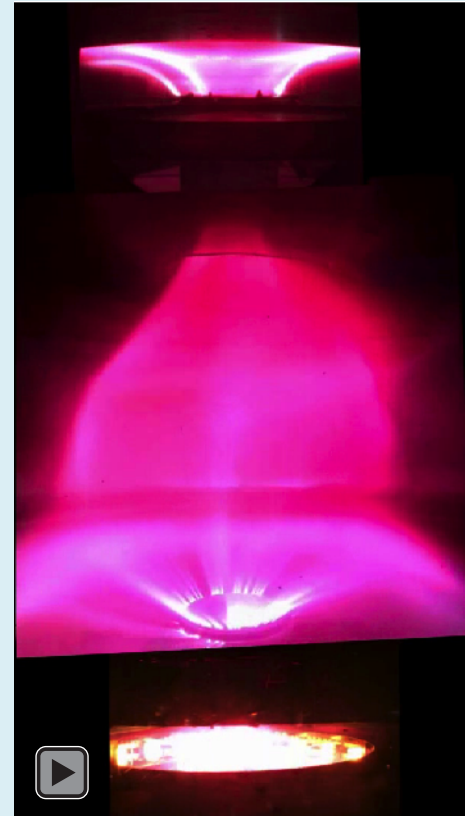
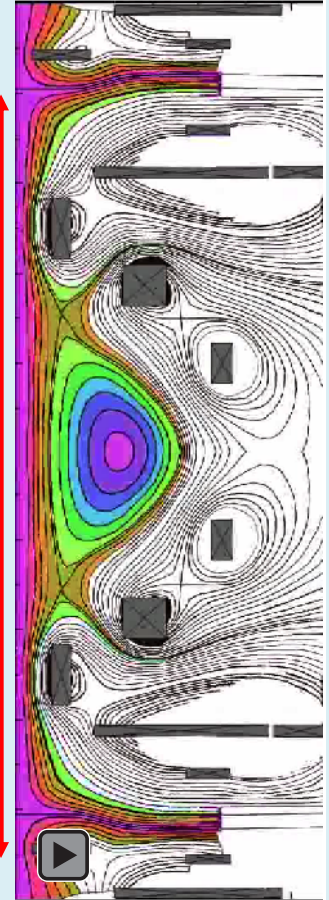
Magnetic
reconnection

DC voltage from anode to cathode
SUSTAINS THE TOROIDAL CURRENT
by Magnetic Reconnections

Magnetic
reconnection

2900° C heated
Cathode

DC voltage



*Maxwell equations do not imply that a DC voltage between electrodes
can sustain a toroidal current: Magnetic Reconnections do the trick!*

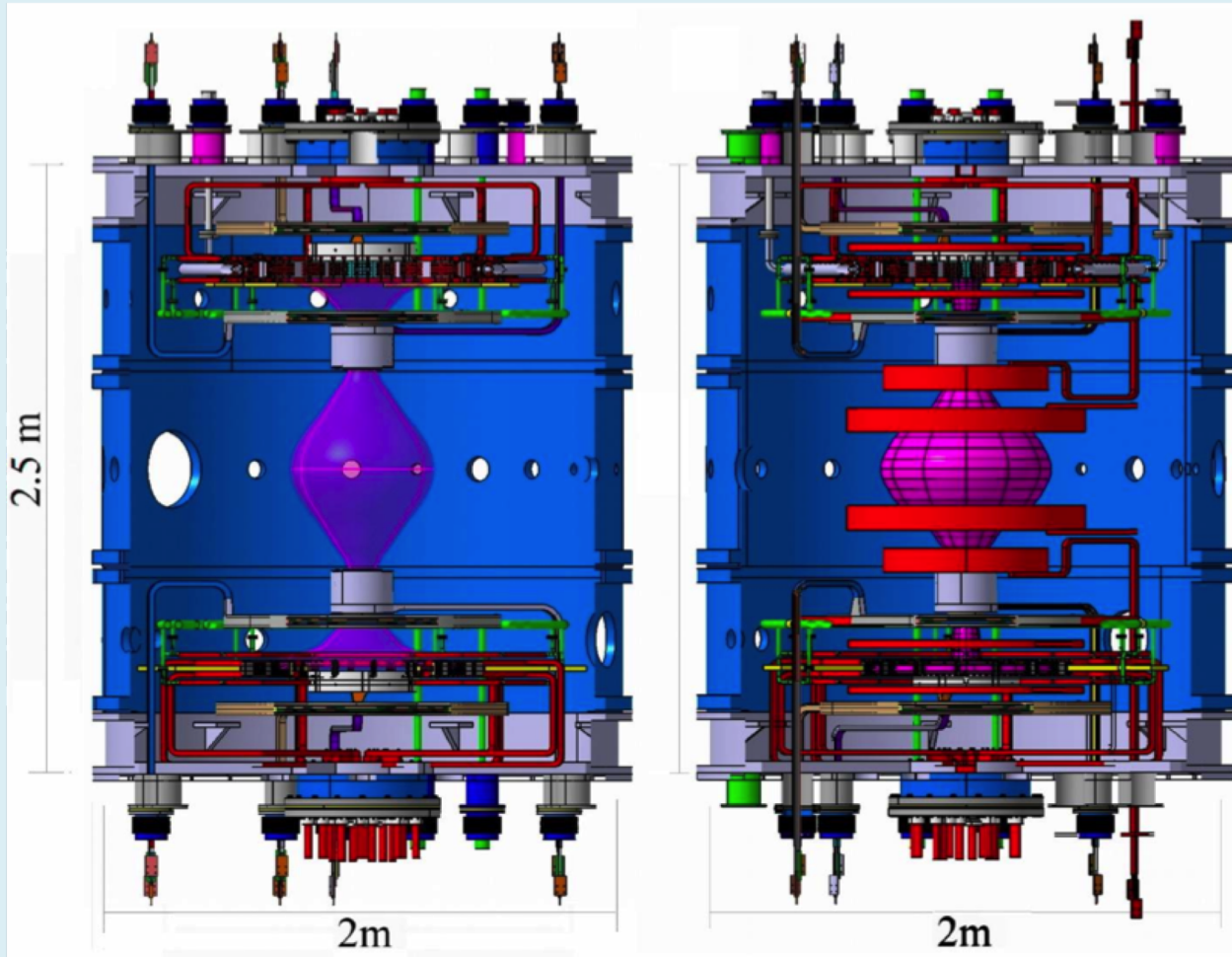
Phase-1 & Phase-2 of the experiment

...as they were originally conceived (2001)

As built 2014, Phase-1:
8 PF coils Group-B shaping coils

Phase-2: 8 PF coils + 6 PF
Group-A compression coils

2016 Phase-1
Argon plasma



Gas-puffed
anode



2900°C
heated cathode

Centerpost $I_e = 10$ kA
...ST current $I_{ST} = 7$ kA...

Centerpost $I_e = 70$ kA
ST current $I_{ST} = 280$ kA

Fight against spurious plasma discharges



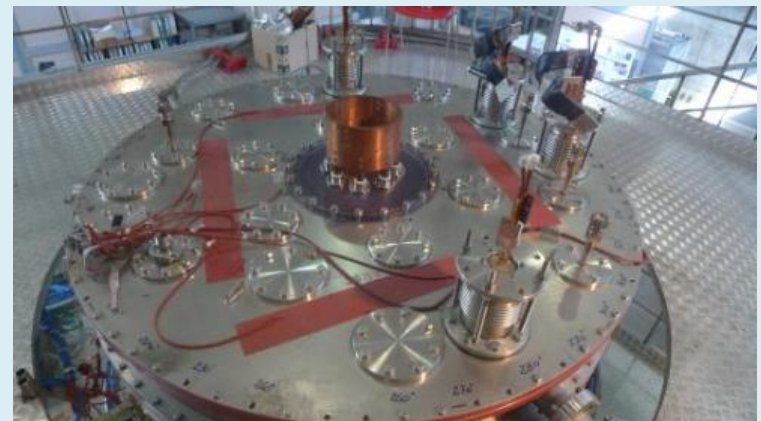
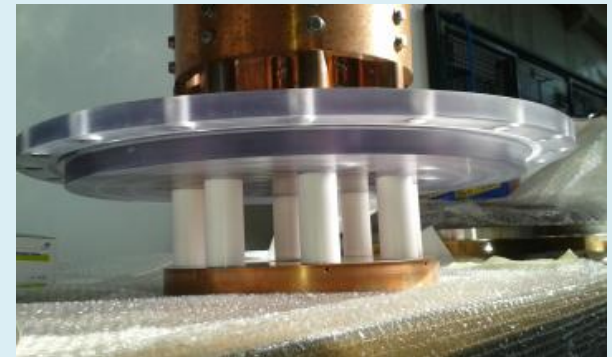
2015/16 experiments produced a heavy metallization on top (anode) & bottom (cathode) bus-bar vacuum entrance flanges, associated with magnetic “nozzles”

June 2016: insertion of Polycarbonate (transparent) bus-bar flanges on top/bottom of machine

*Heavily metallized
top & bottom AISI304 bus-bar flanges*



**4 cm thick Polycarbonate
(required by atmospheric pressure)**

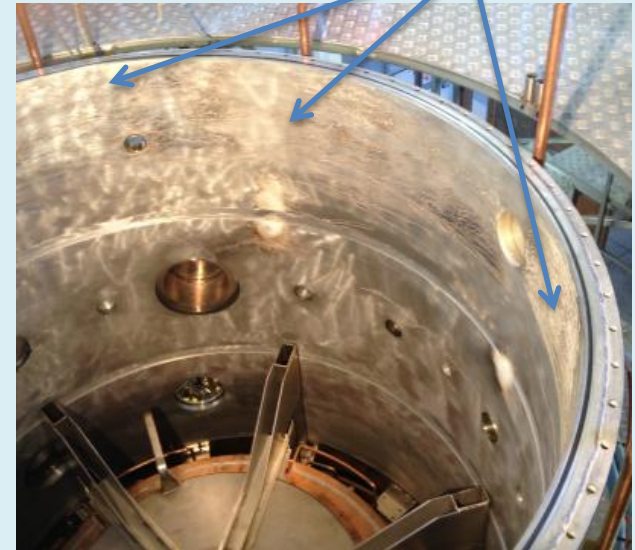


Fight against spurious plasma discharges (cont.)

Secondary discharges from electrodes hitting Al vacuum vessel wall (**plenty of scars!**)



Shot 378 $I_e = 2.7$ kA



Polycarbonate flanges got rid of all metallization from bus-bars:
2mm thick Polycarbonate lining covers the Al vacuum vessel

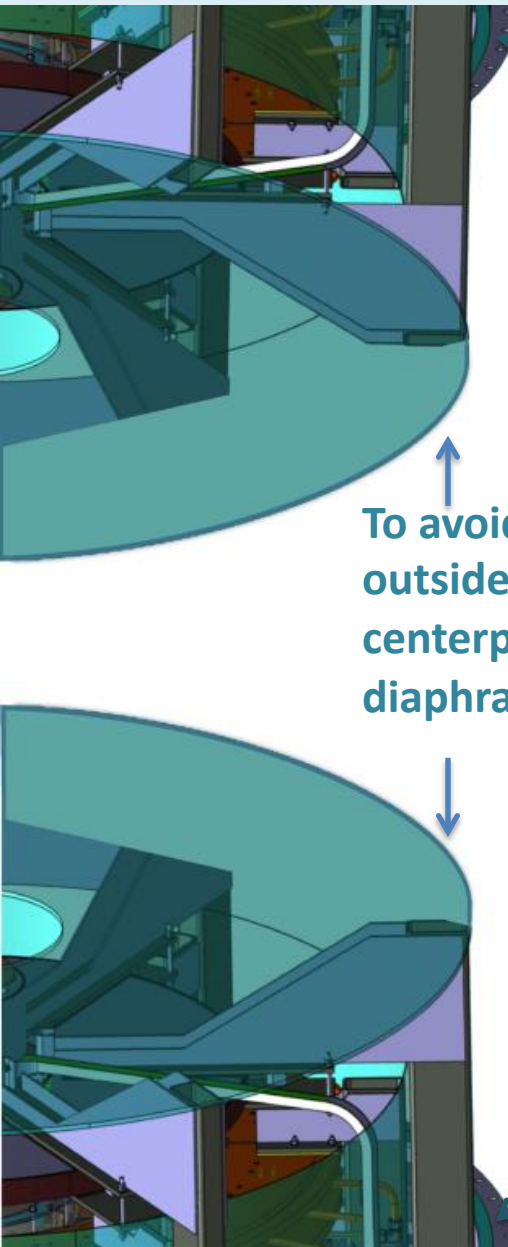


December
2016



secondary
2mm thick
Polycarbonate
screen
surrounds
rear of anode

Fight against spurious plasma discharges (cont.)

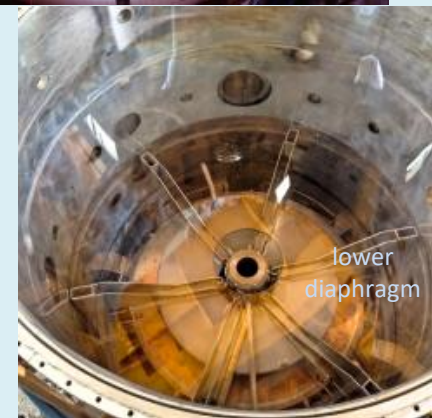


to avoid the bus-bar to vessel current flow an insulating spacer ring has been inserted

To avoid the flowing of plasma currents outside the desired path of the plasma centerpost two large insulating polycarbonate diaphragm separators have been inserted

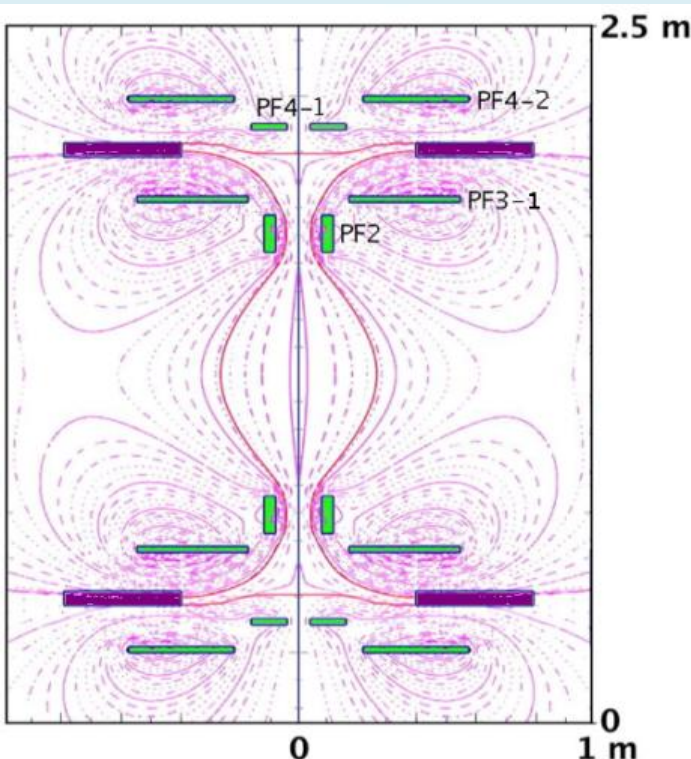
May 2017: Insertion of Polycarbonate lower diaphragm

Lower spacer ring



Rotating Plasma-Centerpost produced 2016-2018

Shaping field inside
4 cm thick Aluminum vessel



January 2018:
objectives of Phase-1 achieved

anode-to-cathode voltage
90 V up to ~200 V at 10 kA

Argon, equator line-averaged
electron density: $\langle n_e \rangle \propto I_e$
 $\langle n_e \rangle = 4 \cdot 10^{20} \text{ m}^{-3}$ at $I_e = 10 \text{ kA}$

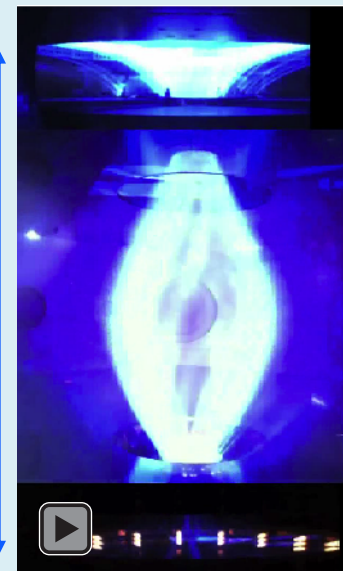
Rotation $\omega \sim 2\pi (500) \text{ radians/sec}$

anode-to-cathode voltage
~320 V down to ~220 V at 10 kA

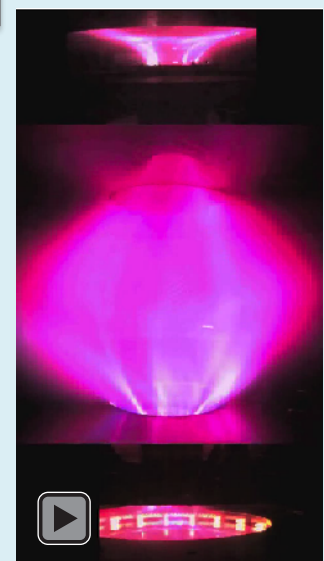
Hydrogen, equator line-averaged
electron density
 $\langle n_e \rangle = 1.5 \cdot 10^{20} \text{ m}^{-3}$ at $I_e = 10 \text{ kA}$

High-field Tokamak densities!

#614



#977



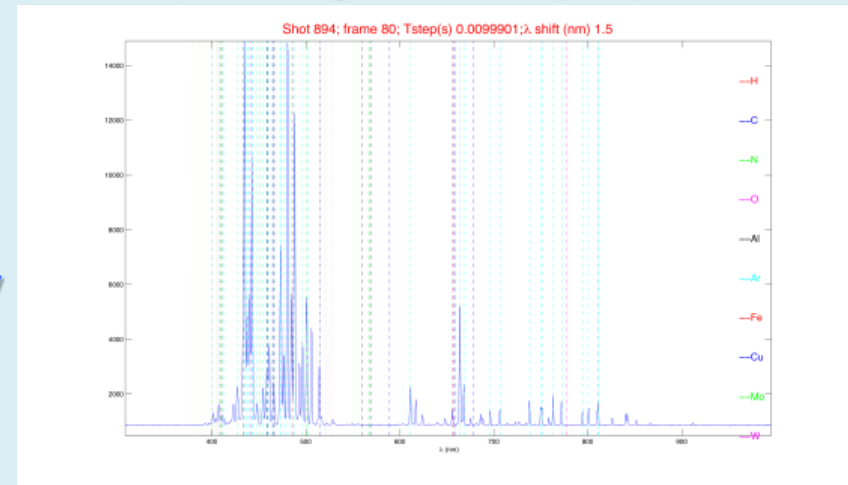
2017 (Argon)

Langmuir probe
measurements give
 $10 \div 3$ eV temperature
 $2 \div 5 \cdot 10^{19} \text{ m}^{-3}$ density
at edge of anodic
plasma mushroom

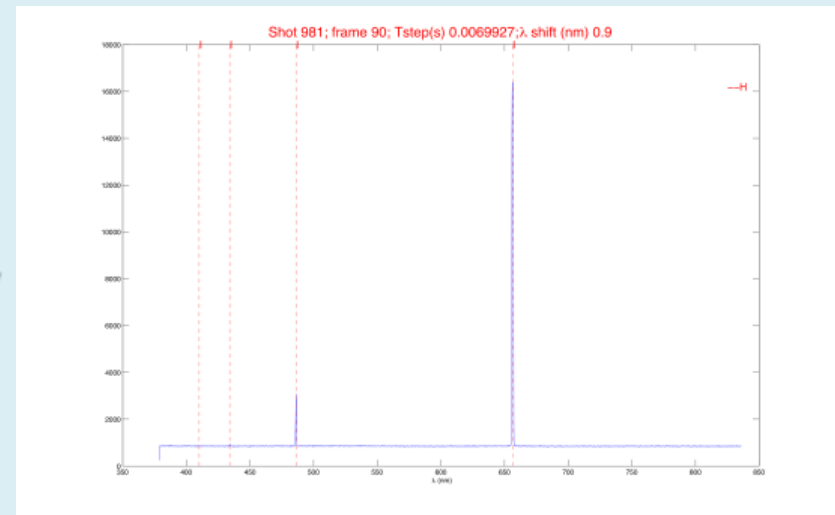


Visible Spettroscopy

2018 (#894, $I_e=8$ kA, Argon)



2018 (#981, $I_e=10$ kA, Hydrogen)



Balmer lines only

No Anode-Arc Anchoring: Electrostatic plasma effects

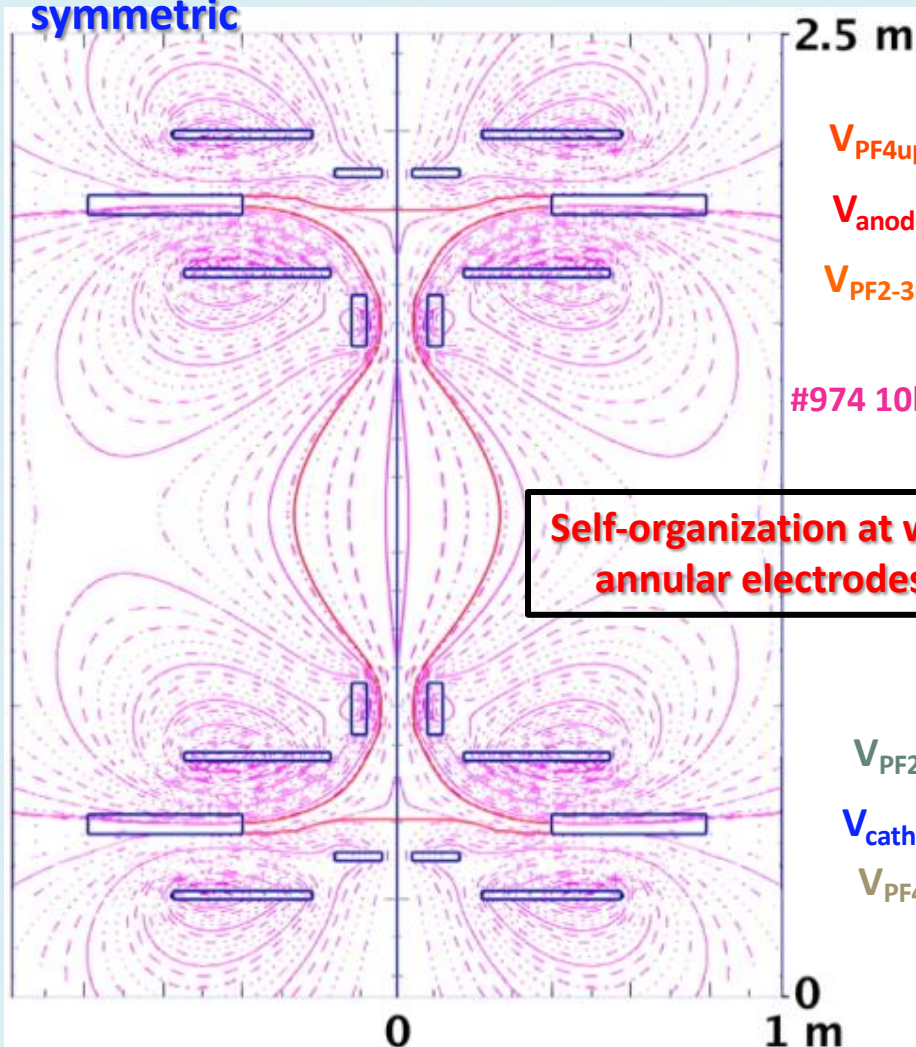
$\vec{E} \wedge \vec{B}$ plasma rotation does the trick!

magnetic field is up\down symmetric
symmetric

but

electrostatic field not up\down

$V_{LidUp} \sim +95 \text{ V}$



$V_{PF4up} \sim +95 \text{ V}$

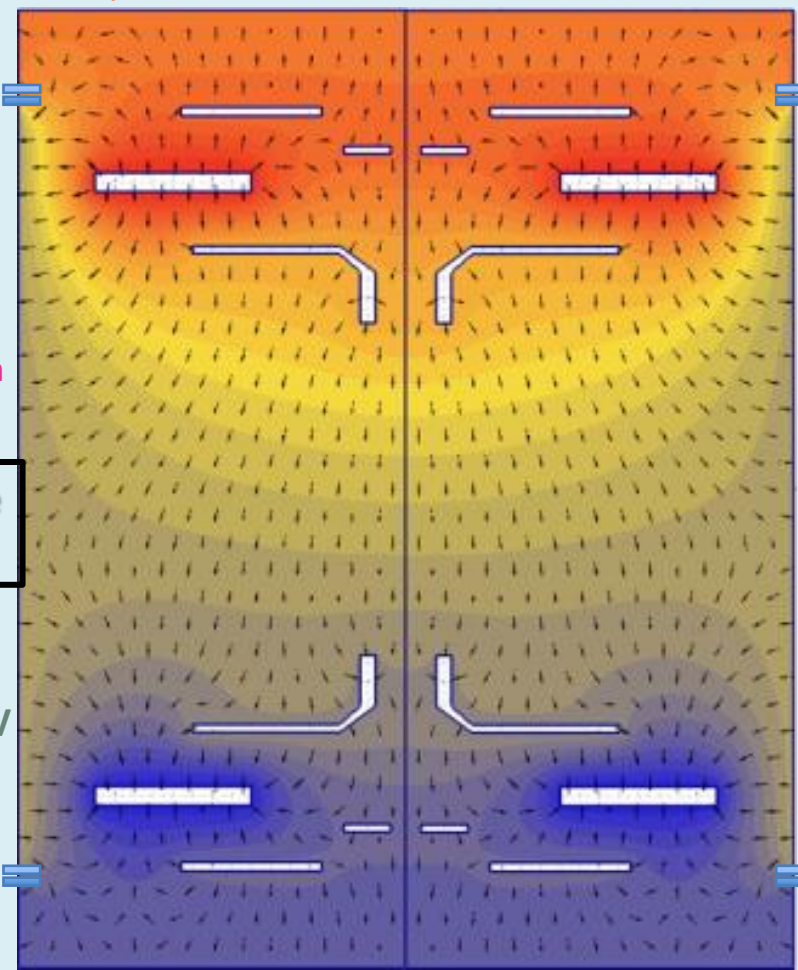
$V_{anode} \sim +139 \text{ V}$

$V_{PF2-3up} \sim +50 \text{ V}$

$V_{PF2-3low} \sim -12 \text{ V}$

$V_{cathode} \sim -80 \text{ V}$

$V_{PF4low} \sim -41 \text{ V}$



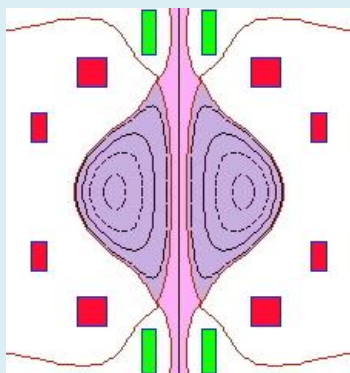
$V_{LidDown} \sim -56 \text{ V}$

Lines: magnetic field

Color contours: electrostatic potential, Arrows: E

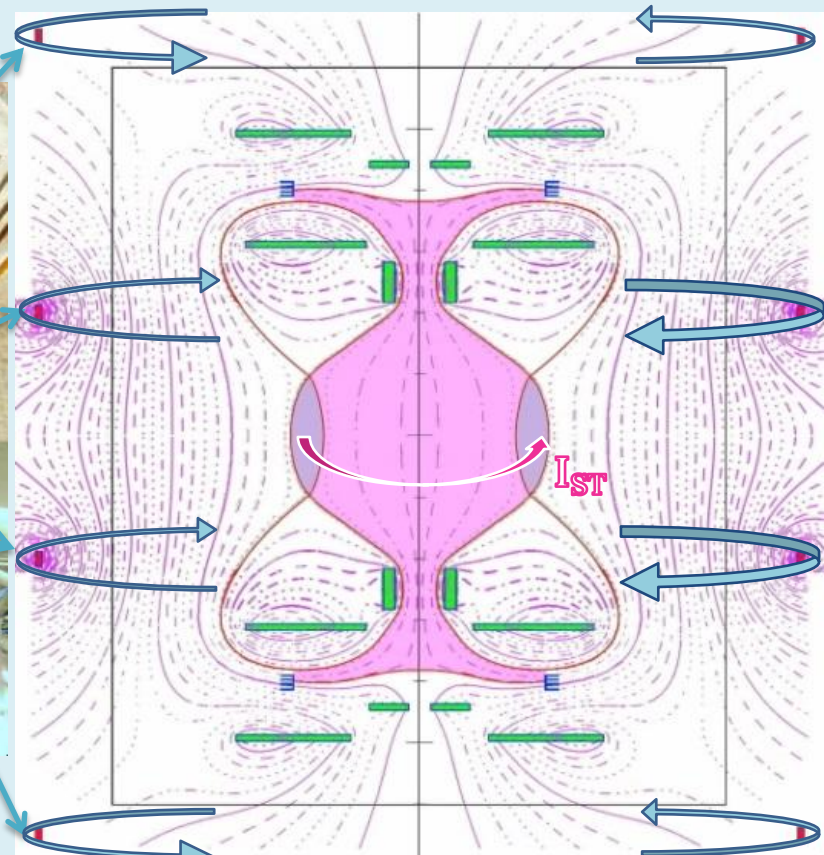
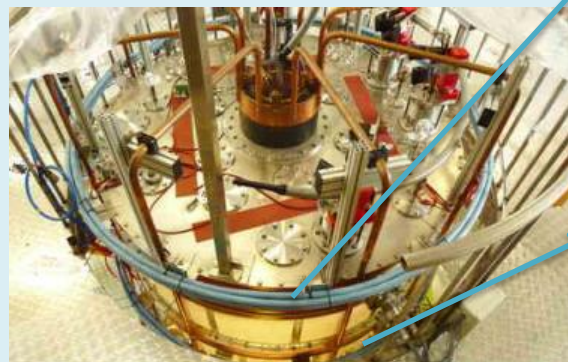
Plasma tori obtained & sustained during year 2018

Phase-2 Spherical Torus:



not feasible without
internal compression coils

A simpler vertical field built-up by adding 4 PFExt coils
external to the vessel



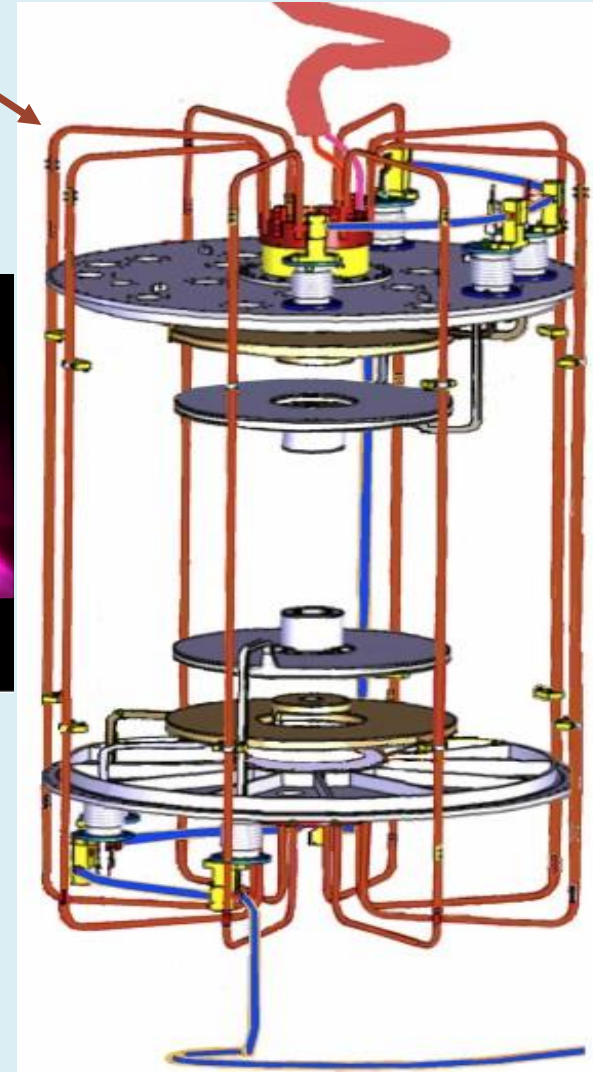
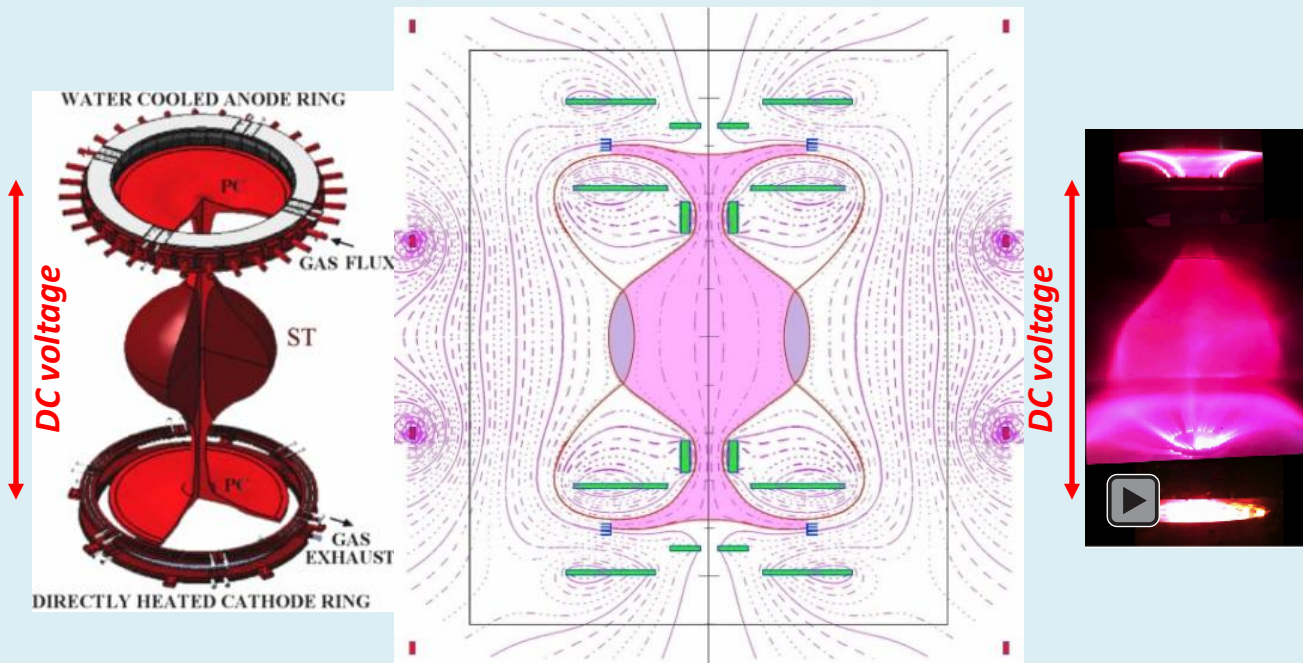
in 2 PFExt near equator
the current flows in opposite direction to
toroidal current inside the Plasma-Centerpost



New PFExt 2019

Plasma fired 0.60s after PF current (skincurrent time, 4 cm thick Al vessel)
torus duration limited to 0.5 sec → magnetostatic field at torus formation

- An axisymmetric high density confined torus is produced in absence of a toroidal magnet: only external metal legs

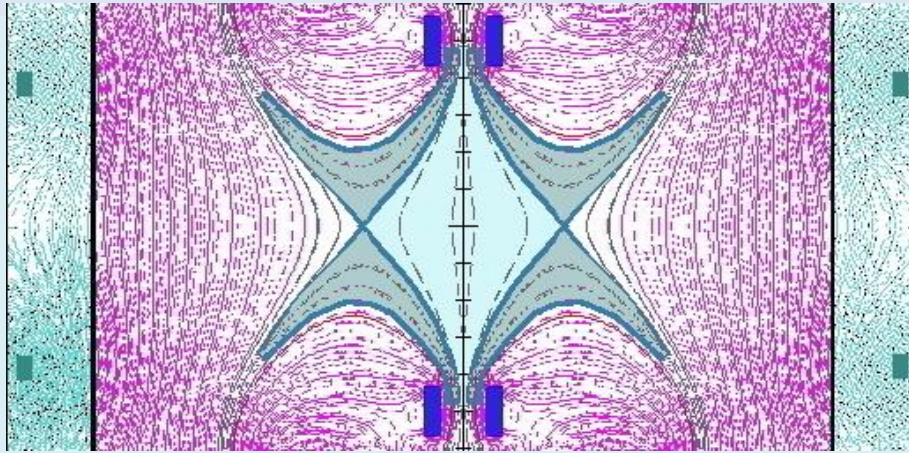


Major surprise: current carrying torus formed & sustained in an external magnetostatic B field

Apart from the field due to the plasma current, driven by the DC voltage, the overall field that confines the torus is purely magnetostatic

March 2018 Torus formed in Argon plasmas

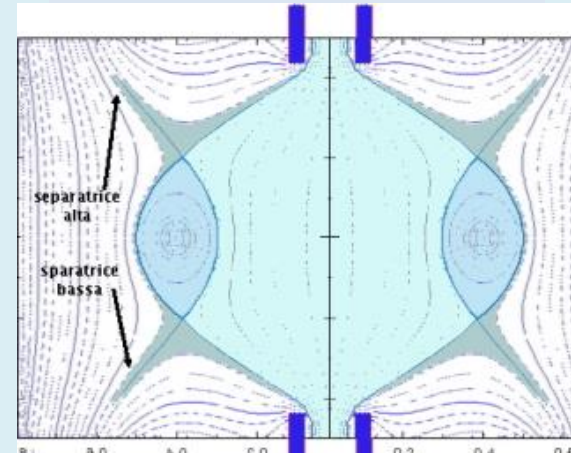
In absence of Torus formation



$I_e = 3$ kA

$I_e = 5$ kA

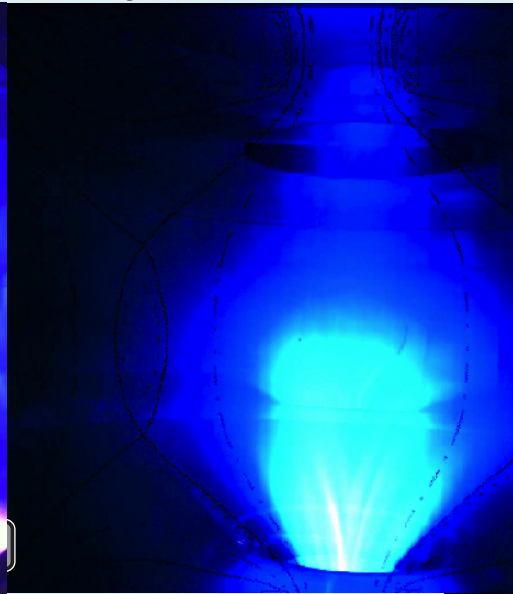
With Torus formation



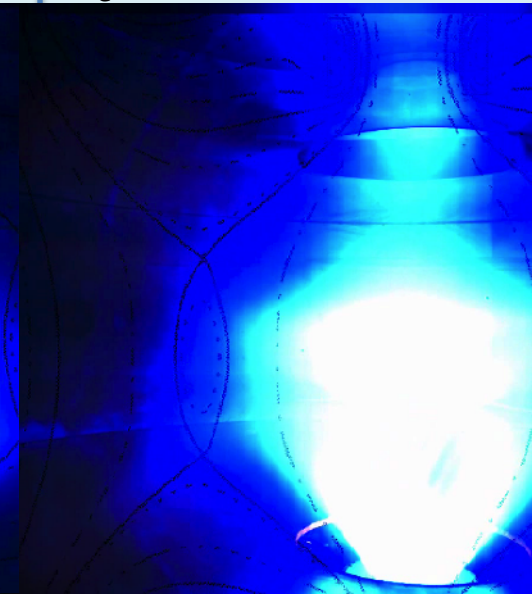
$I_e = 10$ kA



#1098, Argon



#1096, Argon



#1091, Argon

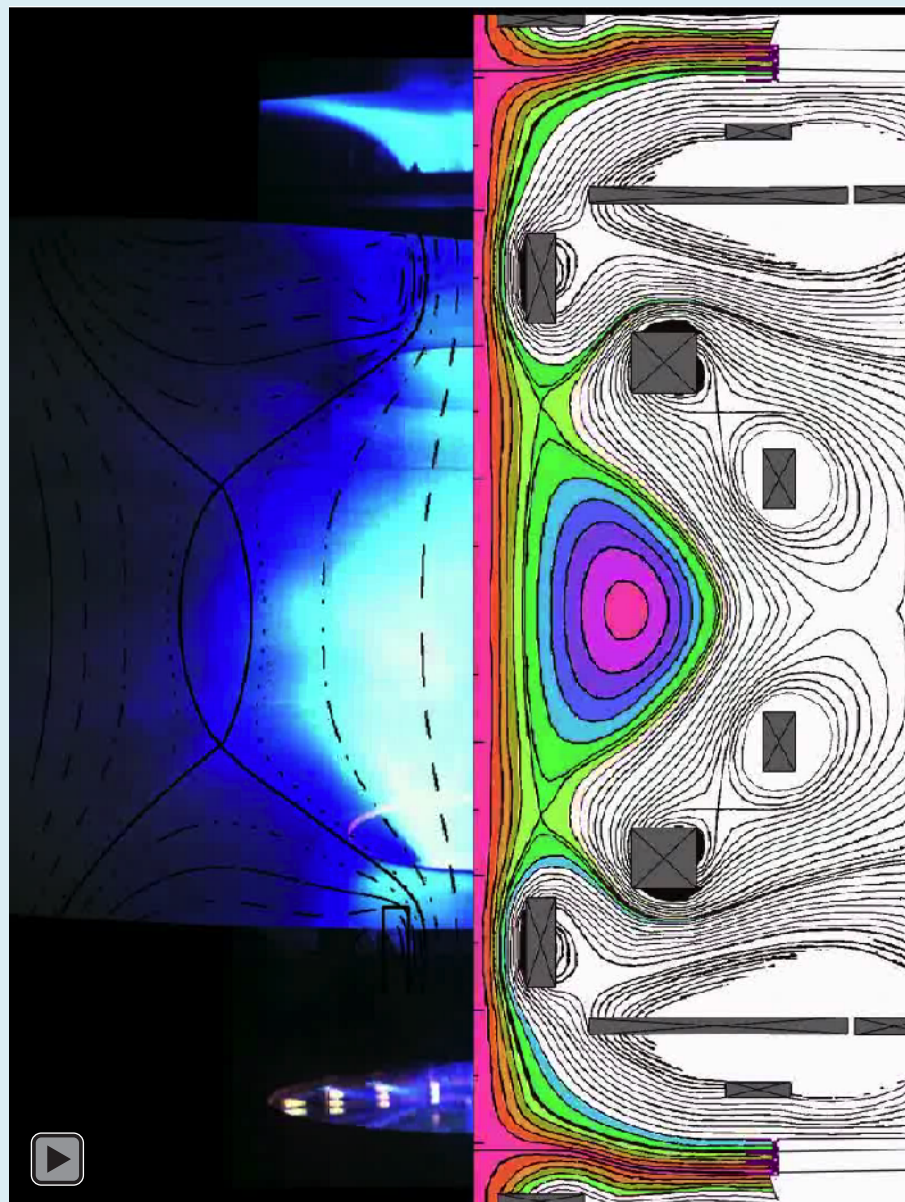
$I_{ST} = 5$ kA

Torus forms at the expected current: $I_e \sim 8$ kA

Argon Torus
break-down $V_e \sim 200$ V
steady $V_e \sim 220$ V

The “gentle Divertor”
of the (barely visible) Argon Torus

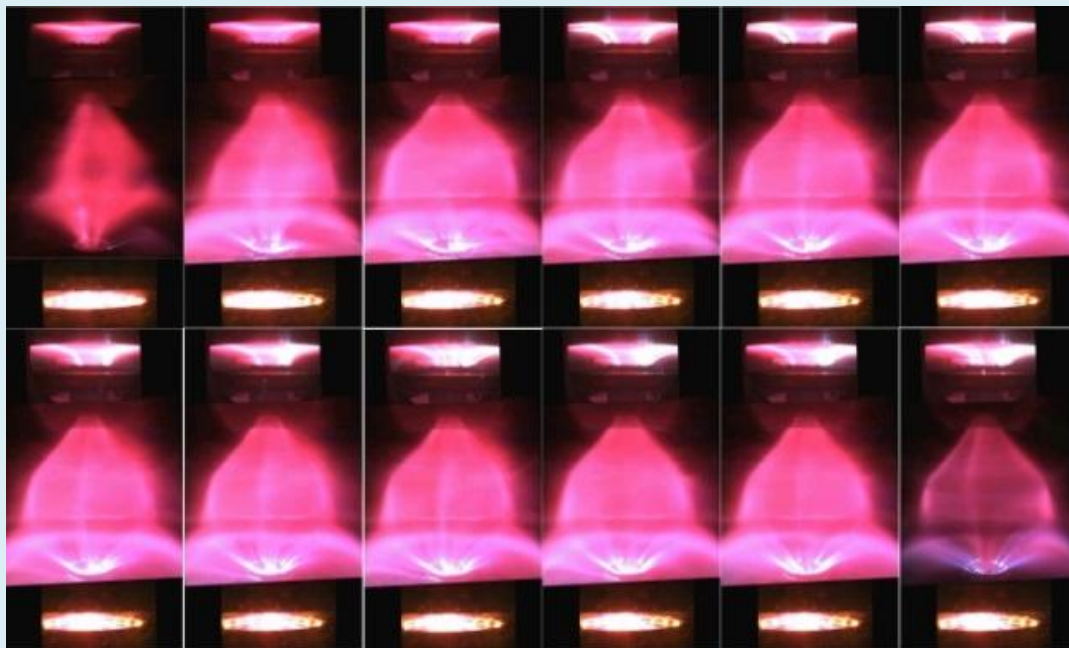
Lower Divertor fan is dominant
& slightly shifts down the Torus



#1160, Argon, X-points fit $I_{ST}=5$ kA

April 2018 Torus formed in Hydrogen Plasma

#1280 with AISI340 divertor plate



break-down ~ 360 V
at 10 kA ~ 250 V

Hydrogen tori have been sustained up to 0.25 sec
(Torus persists till anode-cathode voltage is applied)

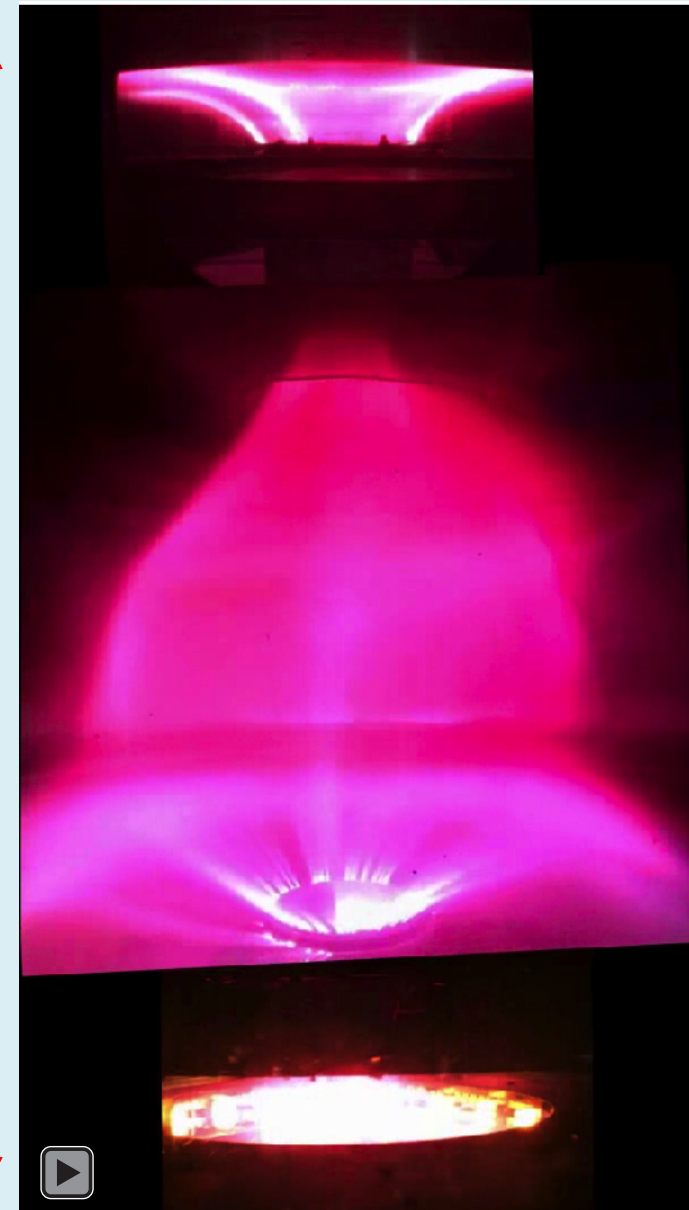
Slim tori aspect-ratio $A=R/a \sim 7$
& elongation $b/a = \kappa \sim 3.5$

...unfeasible in a Tokamak!

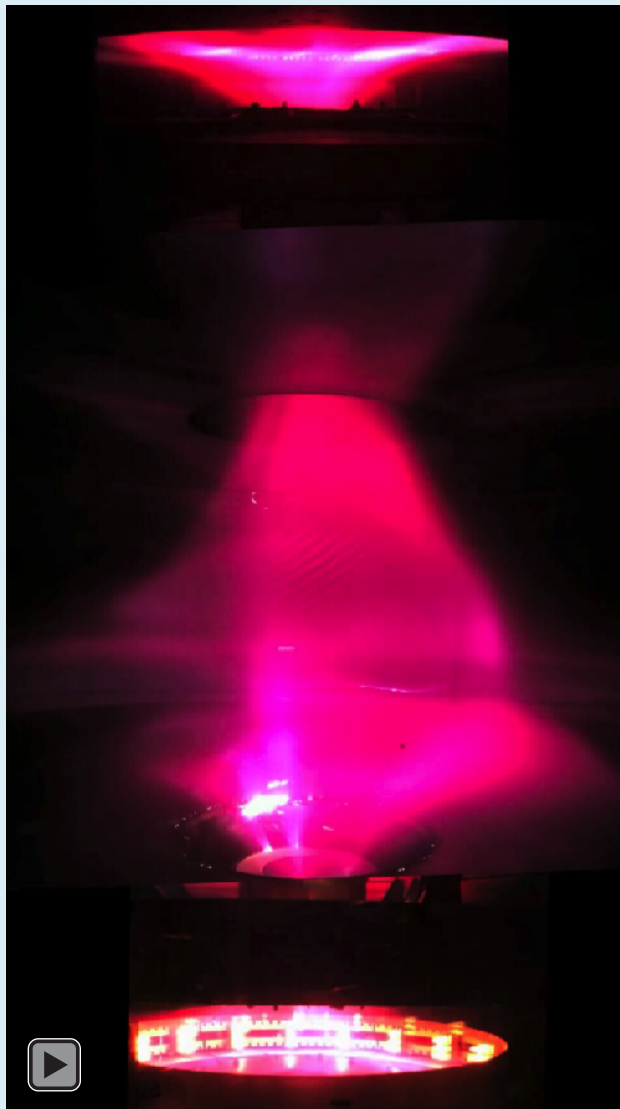
($I_e = 10 \text{ kA}$; $I_{ST} \sim 7 \text{ kA}$)



DC voltage



Torus formed in Hydrogen Plasma (cont.)

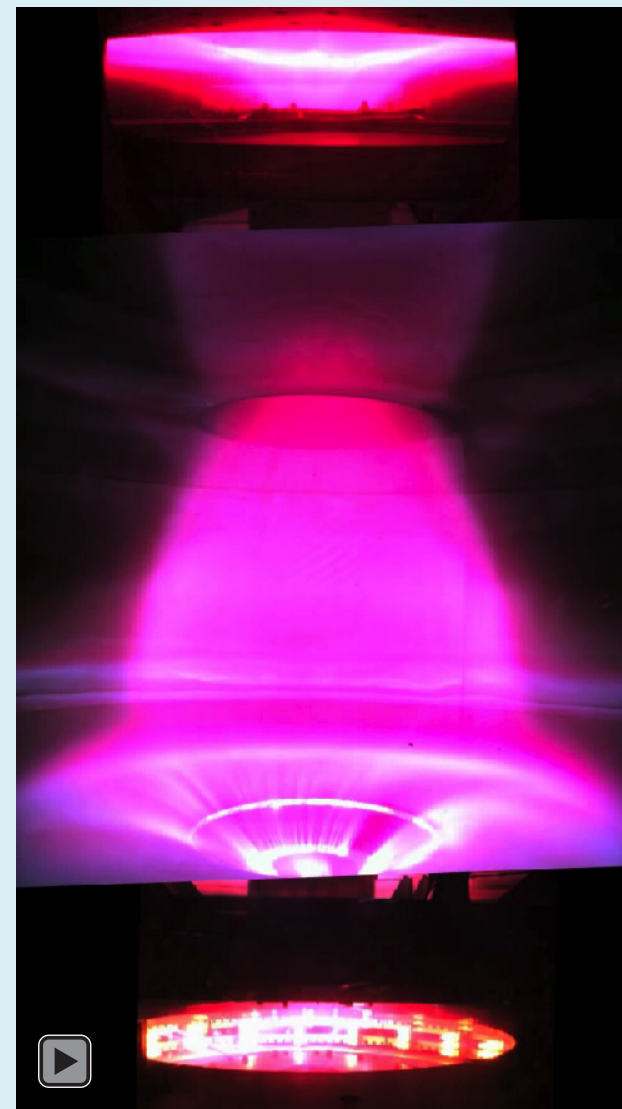


evident at plasma breakdown



#1202, Hydrogen

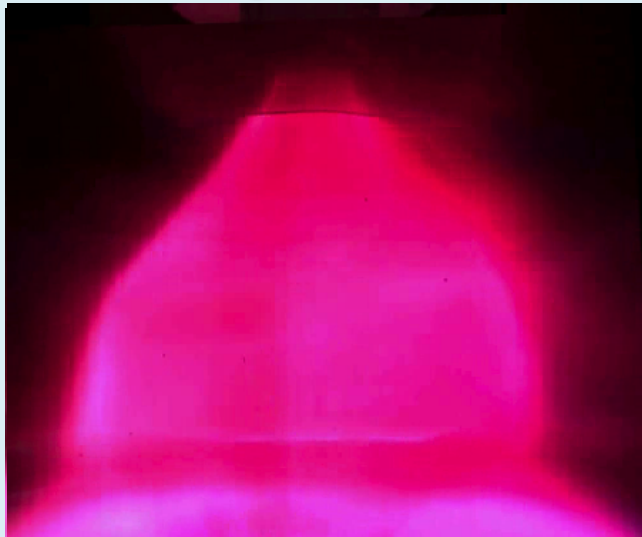
& ...after ¼ sec



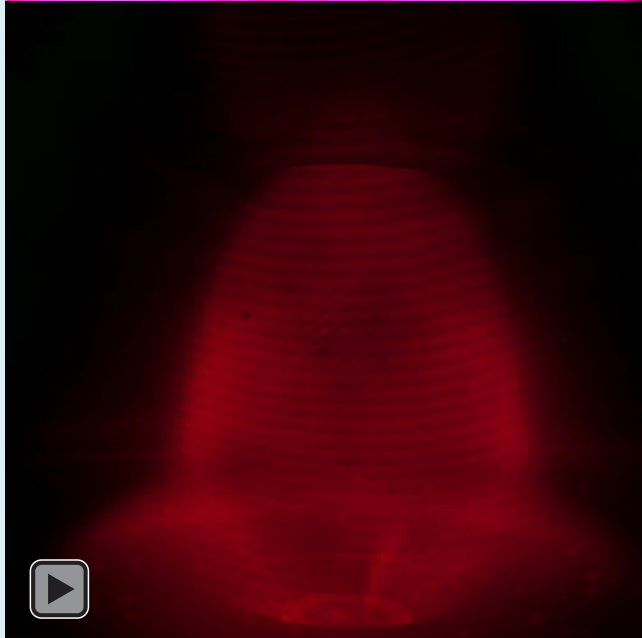
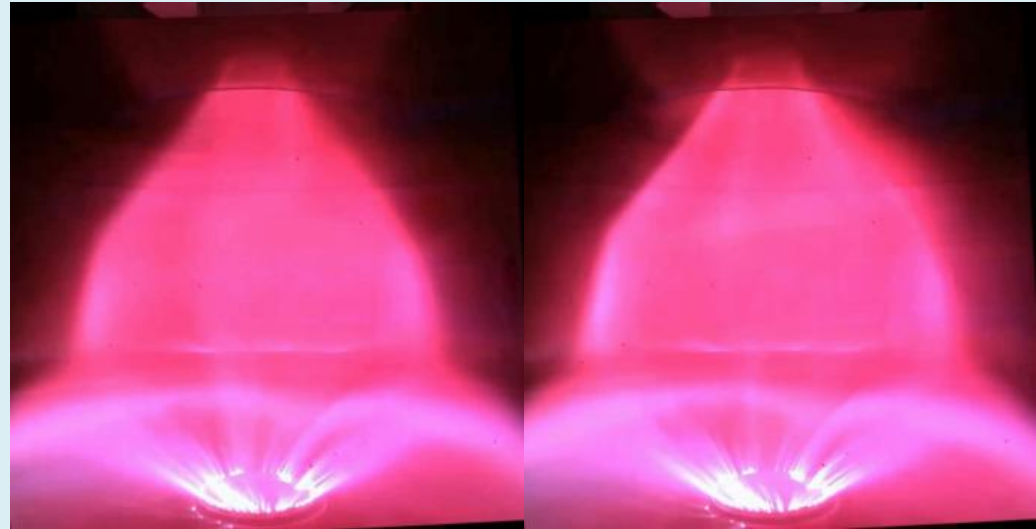
at plasma switch-off

Torus formed in Hydrogen Plasma (cont.)

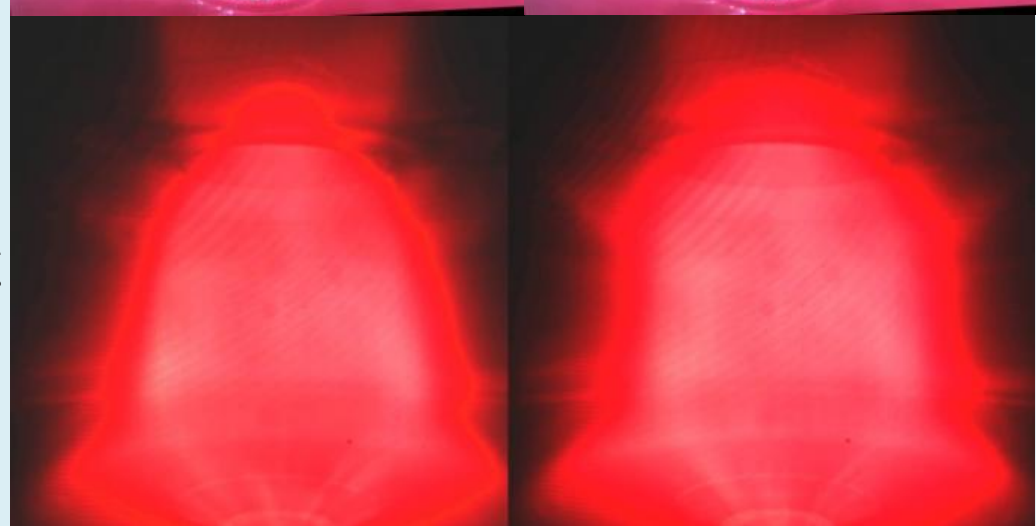
Confining toroidal current injected in pulses every 2-3 ms



#1280
Visible
light



#1219
H-alpha
filter



2D approx. magnetic reconnections at ordinary X-points
3D effects: diffused (ergodic) character of the X-points

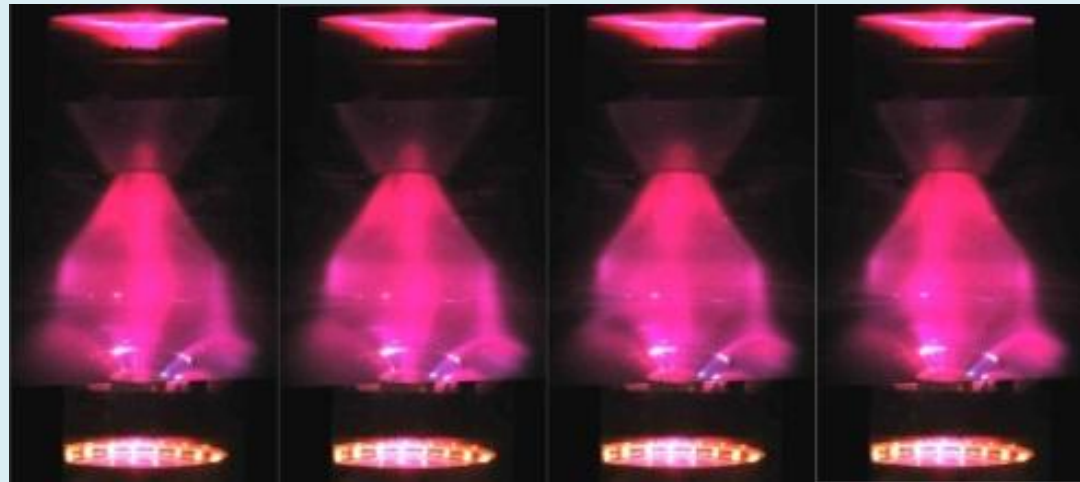


Torus formed in Hydrogen Plasma (cont.)

Appears 5 ms after break-down,
reaches flat-top in ~6 msec

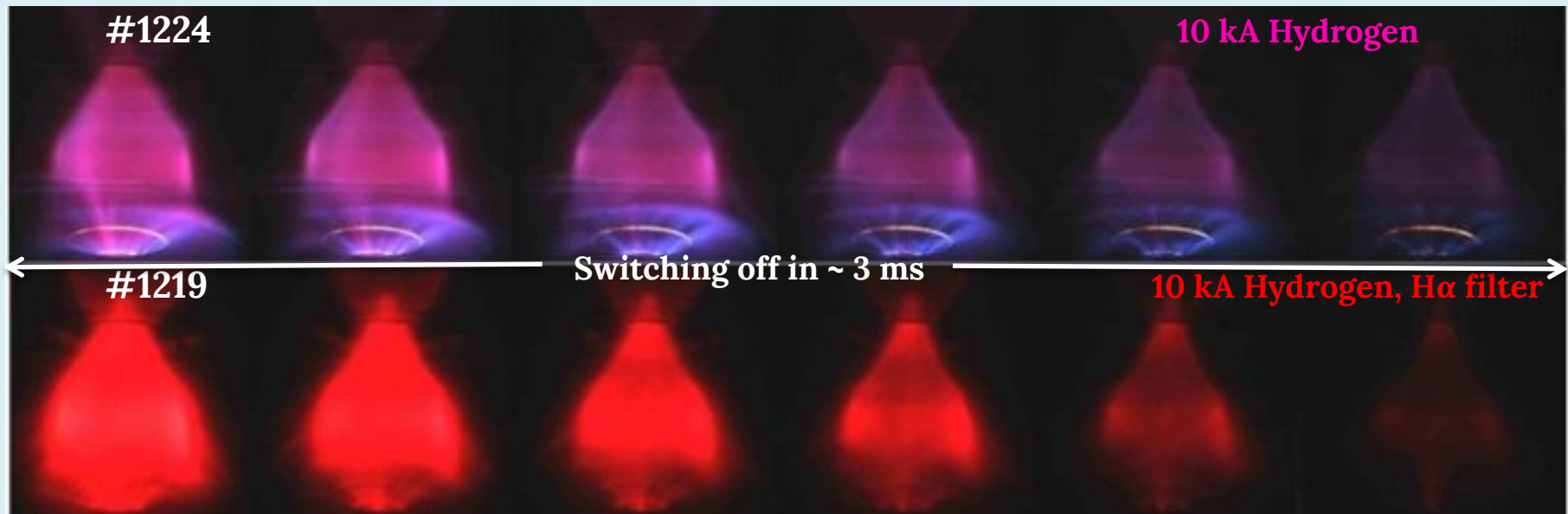
#1202

1 frame
ms



Hydrogen-tori most evident shortly
or during its ramp-down

after the plasma break-down



Toroidal current is confined: the confined toroidal current persists longer than I_e

The dominance of the lower (cathode) divertor fan

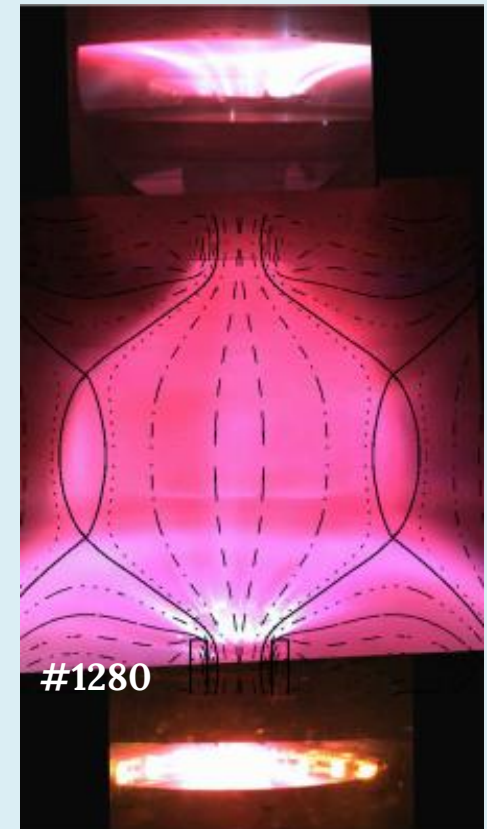
Tori are limited by a magnetic separatrix with 2 conical divertor fans.
In Hydrogen the lower (cathodic) divertor fan divertor is dominant



lower divertor with lower
polycarbonate diaphragm
(April 2018)



lower divertor with lower
AISI304 divertor plate
(July 2018)



fitting the distance between
the 2 X-points of the divertor:
 $I_{ST}=7$ kA in the Hydrogen-torus

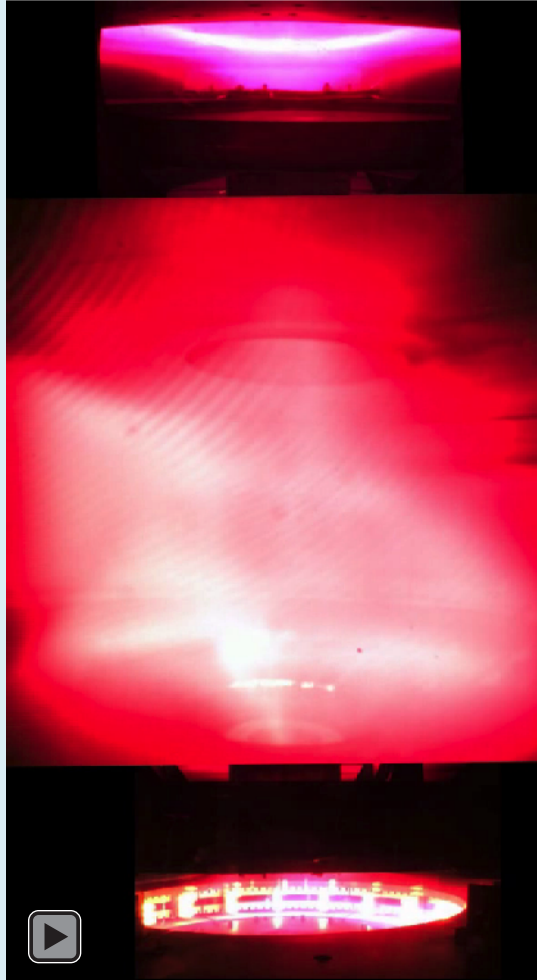
Indeed caused by deterioration of cathode, will be cured at the end of 2019

Torus formed in Hydrogen Plasma (cont.)

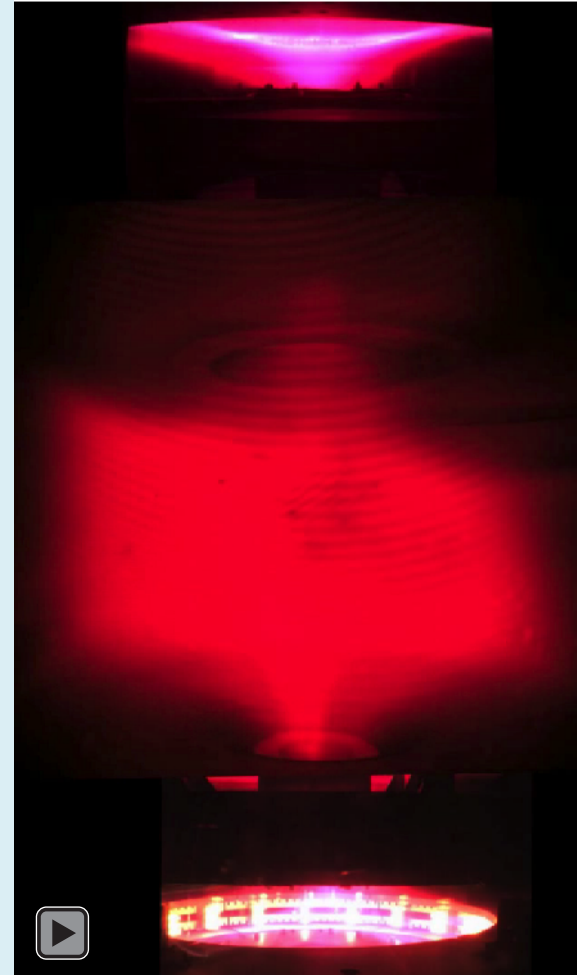
Disruptions gone for good!

Disruptions do not exist, even if plasma does crazy movements, it never vanishes
It can well recover from Multiple Tori, Helical States, Lop-sided Tori

#1219, Hydrogen. $\frac{1}{4}$ s full movie, H α light saturates



#1221, Hydrogen. $\frac{1}{4}$ s full movie, H α light



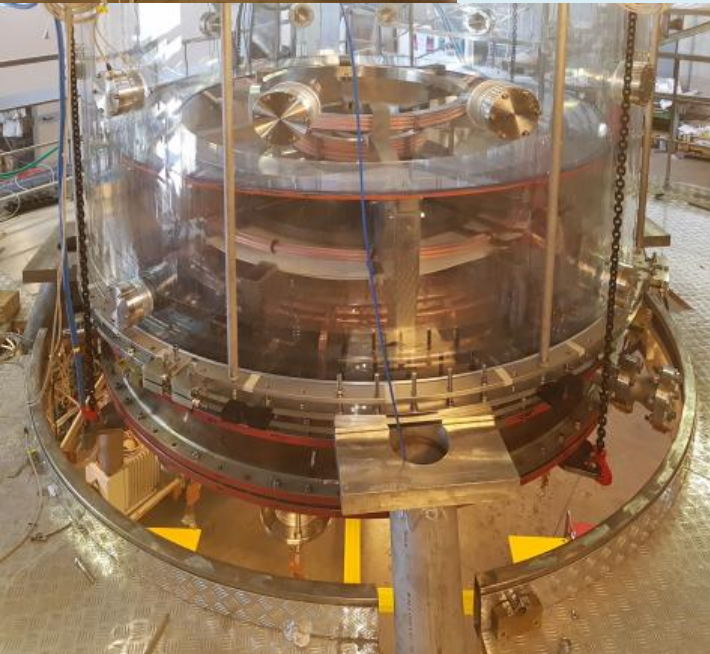
Torus formation remains to be understood Plasma sustainment has to be lengthened to 1 sec

New insulating PMMA Vessel
(no skin effect) Plasma Centerpost
will “slowly” form Tori (in 20 ms)

Reynolds
POLYMER TECHNOLOGY, INC.
Building the Impossible

The gas blanket
around the plasma
will cushion the vessel

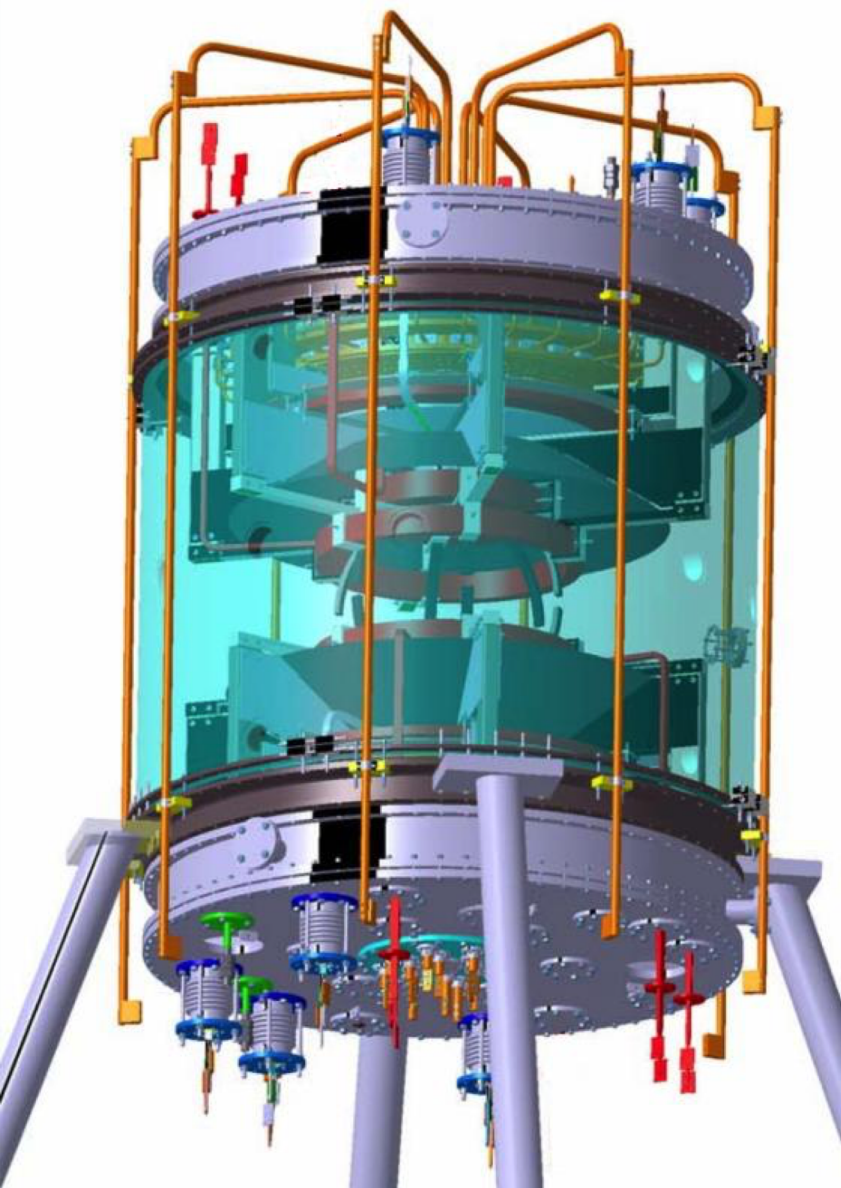
High-vacuum
test (10^{-5} mbar)
successful



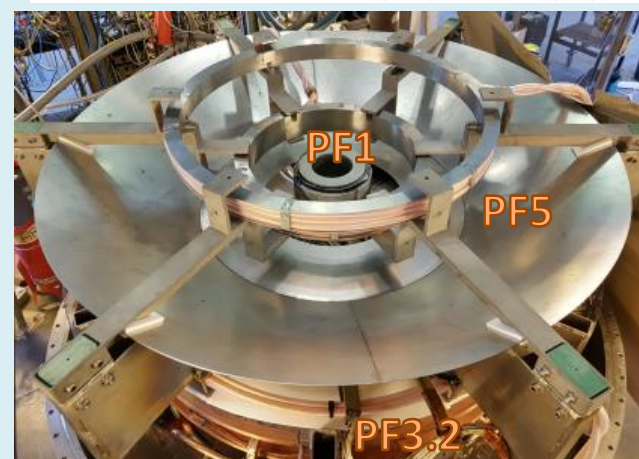
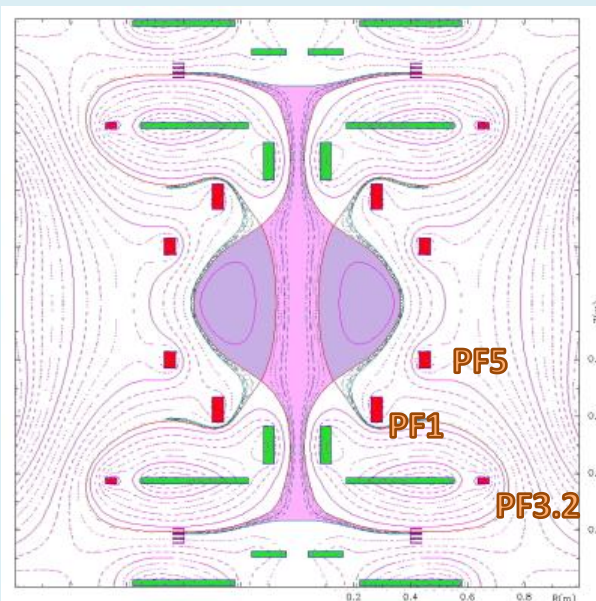
Get rid of prejudice that confined plasma stability requires a metal wall nearby

Phase 1.5: Autumn 2019 6 new compression coils

Try Spherical Tori: $I_e = 10$ kA, $I_{ST} \approx 40$ kA

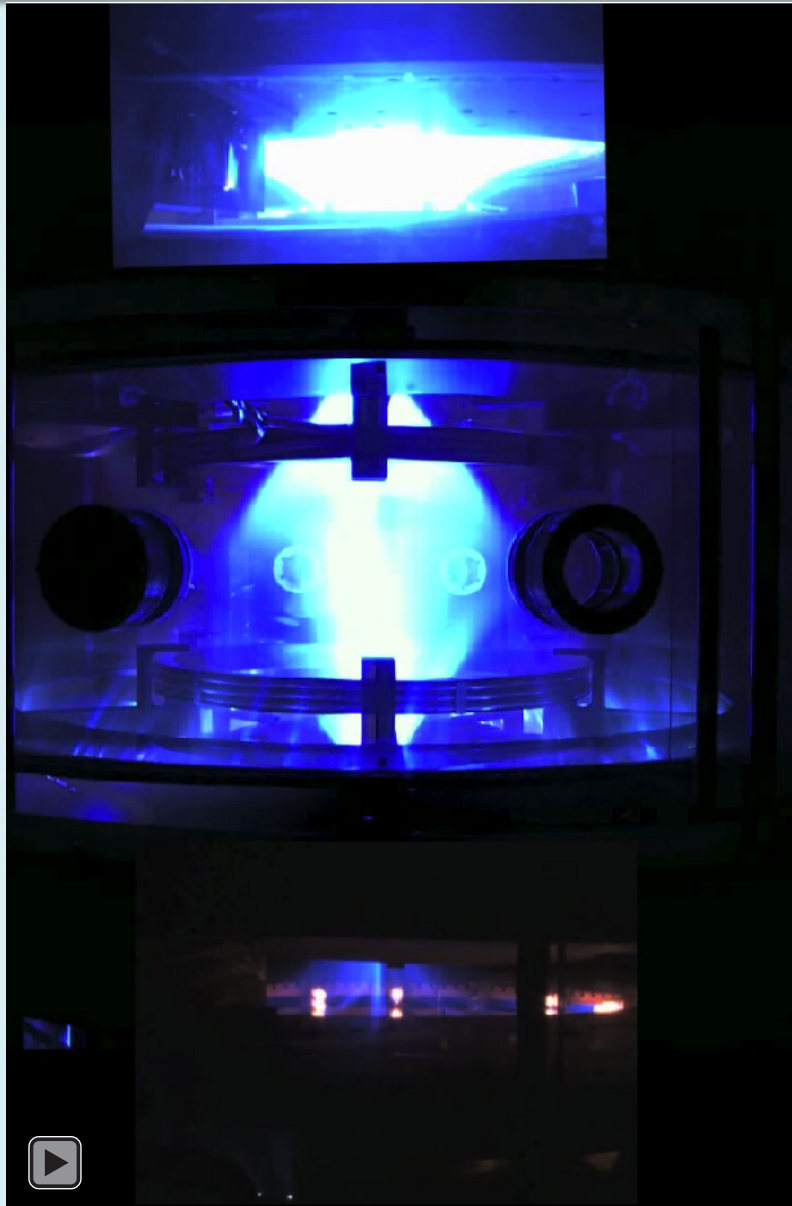


New provisional internal coils:
red copper cable covered with Teflon

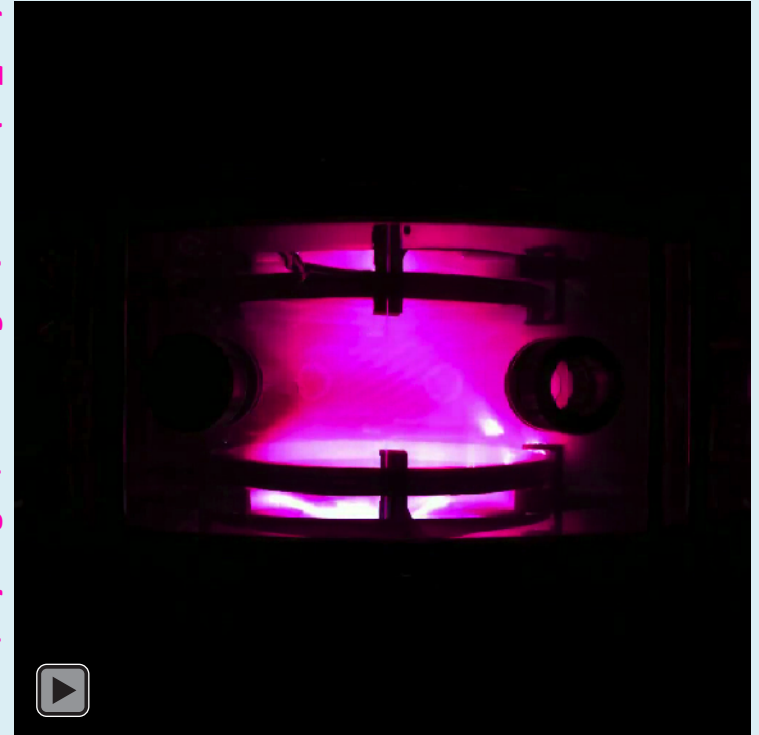


Phase 1.5: some preliminar result (much more in the next talk of Franco Alladio)

#1555, Argon, 0.5 sec: quasi-spherical torus (PF_int)



#1618, Hydrogen, 1 sec: high R/a torus (PF_ext)



Same results as with the Aluminum VV !

Remarks:

- **The machine** does not aim at refining previously achieved results, but to be **ground-breaking**
- Until now **the physics ideas seem sound**: Phase-1 aims were achieved & tori were sustained
- **Technically** it can achieve Phase-2 **without design uncertainties, with limited corrections**
- Until now these **corrections have dealt with boundary conditions** (magnetic & electrostatic)
- The **progress of the machine** must follow a **step by step path**: no hazards, ...no double steps(?)
...btw: complete successfully Phase-1.5 before moving to Phase-2 PF coils & Power Supplies
- Fusion might be a dream, but **magnetic reconnections studies must aim at world excellence**
*...& must accommodate **experiments of astrophysical interest***
- **Excellence in reconnection studies** cannot be achieved without **excellence in diagnostics**



+ Other authors

